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Glacial lakes of the Central and Patagonian Andes

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ABSTRACT

The prevalence and increased frequency of high-magnitude Glacial Lake Outburst Floods (GLOFs) in the Chilean and Argentinean Andes suggests this region will be prone to similar events in the future as glaciers continue to retreat and thin under a warming climate. Despite this situation, monitoring of glacial lake development in this region has been limited, with past investigations only covering relatively small regions of Patagonia. This study presents new glacial lake inventories for 1986, 2000 and 2016, covering the Central Andes, Northern Patagonia and Southern Patagonia. Our aim was to characterise the physical attributes, spatial distribution and temporal development of glacial lakes in these three sub-regions using Landsat satellite imagery and image datasets available in Google Earth and Bing Maps. Glacial lake water volume was also estimated using an empirical area-volume scaling approach. Results reveal that glacial lakes across the study area have increased in number (43%) and areal extent (7%) between 1986 and 2016. Such changes equate to a glacial lake water volume increase of 65 km^3 during the 30-year observation period. However, glacial lake growth and emergence was shown to vary sub-regionally according to localised topography, meteorology, climate change, rate of glacier change and the availability of low gradient ice areas. These and other factors are likely to influence the occurrence of GLOFs in the future. This analysis represents the first large-scale census of glacial lakes in Chile and Argentina and will allow for a better understanding of lake development in this region, as well as, providing a basis for future GLOF risk assessments.

1. Introduction

Glacial lakes are a significant component of many glacierised environments and their development can be indirectly linked to long-term climatic changes (Richardson and Reynolds, 2000; Gardelle et al., 2011; Emmer et al., 2016). Over recent decades, the number and size of glacial lakes in mountain regions has increased in response to widespread glacier retreat and thinning initiated at the end of the Little Ice Age (LIA: ~1850 AD) (Paul et al., 2007; Nie et al., 2013; Carrivick and Quincey, 2014; Wang et al., 2014). Post-LIA, climatic warming has enhanced ice melt, which has led to the development of a large number of glacial lakes behind ice dams, lateral and terminal moraines and within over-deepened de-glaciated valley bottoms. Furthermore, in some instances, glacier thinning and flow stagnation has resulted in the increased formation of supraglacial ponds (Quincey et al., 2005, 2007; Scherler et al., 2011; Salerno et al., 2012; Pellicciotti et al., 2015).

Glacial lakes are important globally and regionally for the following reasons: (1) they represent a considerable water resource (Haeberli et al., 2016), with their current and future storage capacity influencing ice melt contributions to global sea level rise (Loriaux and Casassa, 2013; Carrivick et al., 2016); (2) when in contact with, or dammed by, glaciers they can have negative impacts on glacier mass balance (Benn et al., 2007; Röhl, 2008; Miles et al., 2016); and (3) they are the source of potentially catastrophic outburst floods (known as 'aluviones' in Spanish, 'débâcle' in French, and elsewhere widely referred to as Glacial Lake Outburst Floods (GLOFs)) (Haeberli et al., 1989; Reynolds, 1992; Carrivick and Tweed, 2016) which are considered to be the largest and most extensive glacial hazard in terms of disaster and damage potential (UNEP, 2007). Resulting from the partial or complete failure of ice- and moraine dammed lakes, high-magnitude GLOFs have the ability to travel considerable distances from their source, destabilising steep river valley flanks by undercutting them and inundating downstream areas with large amounts of reworked sediment and debris (Clague and Evans, 2000; Breien et al., 2008; Westoby et al., 2014a). In doing so,

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GLOFs have the potential to destroy valuable infrastructure and agricultural land, and threaten the safety of downstream communities. In South America alone, outburst events have directly caused over 15,000 deaths since the early 1800s (Reynolds, 1992; Carrivick and Tweed, 2016), whilst globally the annual costs of GLOF related damage and mitigation projects are on the order of several 100 million Euros (Kääb et al., 2005a).

Our understanding of the processes that govern glacial lake development and failure has improved in recent decades thanks partly to advances in satellite remote sensing (Huggel et al., 2002; Kääb et al., 2005b; Quincey et al., 2005, 2007; Westoby et al., 2014b). Utilising multi-spectral imagery collected by the Landsat satellite series, for example, glacial lake inventories have been compiled for the Himalayas (Gardelle et al., 2011; Zhang et al., 2015), Western Greenland (Carrivick and Quincey, 2014), the Caucasus Mountains (Stokes et al., 2007) and the Bolivian and Peruvian Andes (Cook et al., 2016; Emmer et al., 2016), which have allowed changes to be monitored since the late 1970s. Together with more detailed investigations using high resolution satellite imagery, aerial photography, field-based observations, DEMs, and numerical flood simulations (e.g. Allen et al., 2008; Worni et al., 2013; Iribarren Anacona et al., 2015a) these glacial lake monitoring efforts have been used to better understand how and why GLOFs occur (e.g. Westoby et al., 2014b), identify lakes that may pose a hazard (e.g. Bolch et al., 2011; Reynolds, 2014; Rounce et al., 2016) and inform the design and implementation of remediation strategies (e.g. Richardson and Reynolds, 2000; Reynolds Geo-Sciences, 2003).

The Chilean and Argentinean Andes contain ~29,356 km^2 of glacier ice (~93% of the total glacier area in South America) (RGI Consortium, 2017). These glacierised environments are increasingly being used for mining purposes, hydropower installations and for tourist activities, bringing people closer to glacial hazards (Dussaillant et al., 2010). Using historic bibliographic records and analysing satellite imagery, Iribarren Anacona et al. (2015b) presented the first detailed description of past GLOF occurrence and distribution throughout the Chilean and Argentinean Andes providing a foundation for wider assessments of GLOF risks in this region. Overall, they estimated that at least 31 glacial lakes have failed in Chile and Argentina since the eighteenth century, producing over 100 GLOF events. Importantly, this study notes that the number of GLOF events in Chile and Argentina has increased over the past three decades, highlighting the need for further investigation of the cryospheric, climatic and geomorphic processes driving this trend.

Due to their sporadic nature, little is known about the specific mechanisms that have triggered GLOFs in Chile and Argentina. However, wider analyses of moraine dam failures in other mountains regions suggest a number of dynamic (e.g. dam failures triggered by mass movements) and self-destructive factors (e.g. dam failure due to build-up of hydrostatic pressure, piping and subsidence through ice melt) (see Clague and Evans, 2000; Richardson and Reynolds, 2000; Rounce et al., 2016). These factors can be influenced by threshold parameters related to moraine dam geometry and the local topographic setting. After analysis of past GLOF events in the region, Iribarren Anacona et al. (2014) concluded that moraine dammed lakes in Patagonia, for example, were more likely to fail if they were in contact with glacier ice and had a dam outlet slope of > 8°. Other studies investigating moraine dam failure susceptibility in the Tien Shan Mountains and the Himalayas have placed an emphasis on lake size and rates of lake expansion (e.g. Bolch et al., 2011; Rounce et al., 2016).

In line with global observations (Carrivick and Tweed, 2016), the majority of the GLOF events in Chile and Argentina have resulted from the failure of ice dammed lakes, many of which have developed beside outlet glaciers of the Northern and Southern Patagonia Icefield (NPI and SPI) (Iribarren Anacona et al., 2014). Unlike moraine dammed lakes, which rarely fail more than once, ice dammed lakes can often fail repeatedly on a regular or irregular basis. Lake Catchet II, which is dammed by Colonia glacier in Southern Patagonia, for example, has drained 14 times since 2008 (Dussaillant et al., 2010; Friesen et al., 2015). The processes that trigger the sudden drainage of ice dammed lakes are complex and have been related to changes in ice thickness, lake bathymetry, sub-glacial water pressure and thermal conditions, amongst other factors (Walder and Costa, 1996; Tweed and Russell, 1999; Gilbert et al., 2012).

The prevalence and increased frequency of high-magnitude GLOFs in the Chilean and Argentinean Andes suggests this region is likely prone to similar events in the future as glaciers continue to retreat and thin. Despite this situation, monitoring of glacial lake development and evolution in Chile and Argentina has been limited, with past investigations only covering relatively small regions of Patagonia (e.g. Loriaux and Casassa (2013), Iribarren Anacona et al. (2014) and Paul and Mölg (2014)). In response to current limitations, this study aims to characterise the physical attributes, spatial distribution and temporal development of glacial lakes in the Central and Patagonian Andes through the use of Landsat satellite imagery (acquired in ~1986, ~2000 and ~2016) and other high-resolution image datasets available in Google Earth and Bing Maps. Additionally, glacial lake water volume will also be estimated using an empirical area-volume scaling approach. This analysis represents the first large-scale census of glacial lakes in Chile and Argentina and will allow for a better understanding of the processes that govern lake development in this region, as well as, providing a basis for future GLOF risk assessments.

2. Glacier change in the Central and Patagonian Andes since the 1980s

The Chilean and Argentinean Andes contain ~16,000 glaciers (RGI Consortium, 2017), the majority of which have receded and thinned since reaching Little Ice Age Maxima (LIAM) sometime between the 16th and 19th Centuries (Harrison et al., 2007; Masiokas et al., 2009; Davies and Glasser, 2012). Our knowledge of more recent glacier fluctuations, since the 1980s for example, is limited by the sparsity of detailed mass balance information with direct observations available for only 22 glaciers across the Andes (Mernild et al., 2015). Beginning in 1975, Glaciar Echaurren Norte, located in the Central Chilean Andes, has the longest direct mass balance record available for the Andes Cordillera. These records indicate a large cumulative mass loss during the past four decades, particularly during the 1990s and the late 2000s (Masiokas et al., 2016). Periods of sustained positive mass balances, however, were recorded during the 1980s and early 2000s. The mass balance fluctuations observed for Glaciar Echaurren Norte have been shown to closely match mass balance observations, frontal length fluctuations and long-term glacier velocity measurements reported for other glaciers in the Central Andes but are unlikely to be representative of glacier behaviour further south in Patagonia (Llorens, 2002; Masiokas et al., 2009; Schaefer et al., 2015; Masiokas et al., 2016; Wilson et al., 2016b). An energy balance simulation presented by Mernild et al. (2016), for example, suggests positive mean annual surface mass balances for both the NPI and SPI between 1979/80 and 2013/14, with observed thinning and retreat of outlet glaciers being governed instead by frontal calving dynamics. The availability of historic aerial photography, declassified spy satellite imagery (e.g. Corona and Hexagon) and image datasets from continuous satellite sensor platforms (e.g. Landsat and Terra ASTER) has enabled the relatively long-term monitoring of area change for a number of glaciers across the Andes. Table 1 summarises five large-scale studies that have monitored glacier area change in the Central and Patagonian Andes since the 1950/80s. Overall, glacier area reductions of at least 0.1% a^{-1} are shown for each of the glacier samples monitored, however, regional differences are evident. Relatively heightened rates of area reductions, for example, are shown for glaciers in the Central Andes and the mountain glaciers of South Patagonia sampled by Masiokas et al. (2015) (0.4%–0.6% a^{-1}). In comparison, the rate of area change is lower for samples that include the large outlet glaciers of the NPI and SPI (0.1%–0.3% a^{-1}) (e.g. Davies and Glasser, 2012; Casassa et al.,

Table 1
Glacier area change in the Central and Patagonian Andes since the 1950s.

Region	Study	Spatial extent (TL, BR[a])	Data source	Number of glaciers	Temporal rate of area change (% a^{-1})
Central Andes	Bown et al., 2008	32.4°S, 70.52°W; 33.2°S, 69.97°W	Aerial photography and Terra ASTER satellite imagery	159	1955–2003: −0.4
	Malmros et al., 2016	32.9°S, 70.22°W; 33.36°S, 69.99°W	Aerial photography (1955) and Landsat TM (1989) and OLI (2013/14) satellite imagery	~300	1955–2013/14: −0.5 1955–1989: −0.6 1989–2013/14: −0.5
Northern and Southern Patagonia	Paul and Mölg, 2014	40.99°S, 72.68°W; 44.05°S, 71.70°W	Landsat TM (1985) and ETM+ (2000, 2011) satellite imagery	1290	1985–2011: −1.0 1985–2000: −1.4 2000–2011: −0.5
	Davies and Glasser, 2012	40.89°S, 73.13°W; 55.47°S, 67.88°W	Landsat TM (1985) and ETM+ (2001, 2011) satellite imagery	626	1986–2011: −0.2 1986–2001: −0.1 2001–2011: −0.2
	Davies and Glasser, 2012	46.37°S, 74.03°W; 47.61°S, 73.01°W (NPI)	Landsat TM (1985) and ETM+ (2001, 2011) satellite imagery	44	1986–2011: −0.2 1986–2001: −0.1 2001–2011: −0.2
	Davies and Glasser, 2012	48.17°S, 74.11°W; 51.34°S, 72.85°W (SPI)	Landsat TM (1985) and ETM+ (2001, 2011) satellite imagery	154	1986–2011: −0.1 1986–2001: −0.1 2001–2011: −0.1
	Casassa et al., 2014	48.17°S, 74.11°W; 51.34°S, 72.85°W (SPI)	Landsat TM (1986) and ETM+ (2001) satellite imagery	48	1986–2001: −0.3
	Masiokas et al., 2015	48.9°S, 73.15°W; 49.46°S, 72.57°W	Terra ASTER (2005) and KH-9 Hexagon (1979) satellite imagery	248	1979–2005: −0.6

[a] Top left (TL) and bottom right (BR) of bounding box.

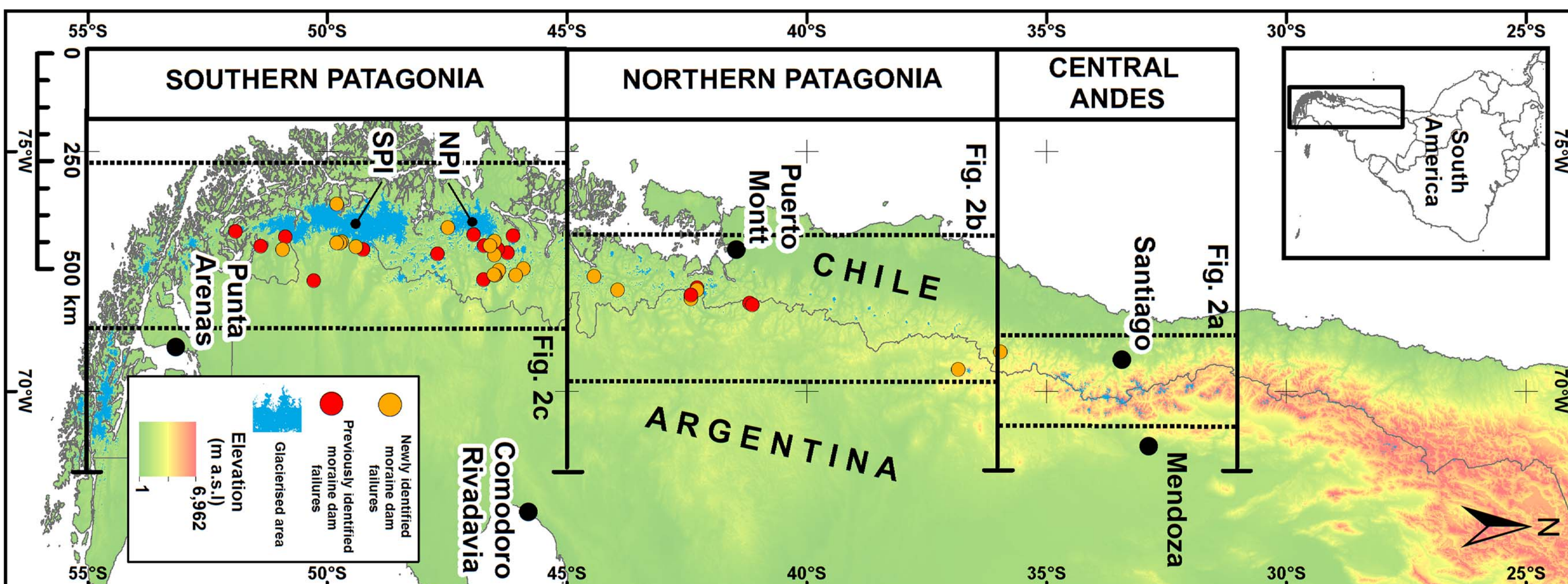

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Fig. 1. Spatial distribution of the Central Andes, Northern Patagonia and Southern Patagonia sub-regions. Locations of GLOF events initiated by moraine-dammed failures identified in this study are indicated by orange markers, whilst those identified by Iribarren Anacona et al. (2015b) and Colavitto et al. (2012) are indicated by red markers. Glacierised areas are shown in light blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2014). The largest rates of area change were observed for glaciers sampled in Northern Patagonia, equating to 1% a^{-1} between 1985 and 2011. The glacier area changes observed for Northern Patagonia have been described as extreme compared to other glacierised regions in the world (Paul and Mölg, 2014).

3. Study area: Central and Patagonian Andes

Our glacial lake analysis was split into the following three sub-regions of the Chilean and Argentinean Andes: the Central Andes (31°–36°S), the Northern Patagonian Andes (36°–45°S) and the Southern Patagonian Andes (45°–55°S).Throughout this study, the latter two sub-regions are referred to separately as Southern and Northern Patagonia and collectively as the Patagonian Andes (Figs. 1 & 2). These three sub-regions were chosen in accordance to the climatic sub-divisions proposed by Masiokas et al. (2009) (based on Lliboutry, 1998) and include 92% of the glaciers contained in the Chilean and Argentinean Andes (RGI Consortium, 2017). The climate and topography of the Andes between 31° and 55°S varies considerably creating differing glacierised environments. In the Central Andes, the climate is semiarid and Mediterranean in type with the majority of precipitation occurring during the austral winter. This high mountainous region has an average altitude of ~3,500 m (Masiokas et al., 2016) and contains ~1650 glaciers (RGI Consortium, 2017) ranging from relatively small cirque-type glaciers to larger valley glaciers (e.g. Universidad Glacier - 28.1 km^2 (Wilson et al., 2016b)). The Central Andes also contain a large number of rock glaciers, which together with debris-covered glaciers make up ~36% of total glacierised area (Janke et al., 2015). South of the Central Andes, the climate gradually becomes more humid and maritime with precipitation in mountainous areas increasing sharply from ~500 mm a^{-1} to a maximum of ~5,000–6000 mm a^{-1} on the SPI (50°S) (Escobar et al., 1992; Masiokas et al., 2009). With the main Andean divide blocking the passage of frontal systems moving in from the Pacific, a strong west-east precipitation gradient also exists and, as a result, the eastern Andes receives reduced precipitation and is less glacierised (Masiokas et al., 2008). Between 35° and 42°S, glaciation is limited by elevation and mild air temperatures, with ice only occurring on isolated volcanoes. However, the high levels of precipitation and increased relief of the Andes further south (~1,500–2000 m a.s.l) has facilitated the growth of large glaciated areas dominated principally by the NPI and SPI, which cover 3976 km^2 and 13,219 km^2, respectively (Davies and Glasser, 2012).

Glacier retreat and thinning observed throughout the Andes has been widely associated with climatic warming and reduced precipitation (Rosenblüth et al., 1997; Rivera et al., 2002; Villalba et al., 2005; Masiokas et al., 2009; Masiokas et al., 2016). However, the magnitude and timing of these climatic changes in the Central and Patagonian Andes vary and analyses of long-term trends are limited by the lack of high elevation meteorological stations, particularly across Patagonia (Masiokas et al., 2008). In the Central Andes, for example, air temperature has been estimated to have increased by ~0.25 °C/decade between 1975 and 2001 (Rosenblüth et al., 1997; Falvey and Garreaud, 2009), which has resulted in a rise of the winter 0 °C isotherm by ~120 m (Carrasco et al., 2005). In comparison, an upper troposphere warming trend of 0.019–0.031 °C a^{-1} has been detected in Northern Patagonia between 1985 and 2000 (Bown and Rivera, 2007). Furthermore, tree ring analyses performed between 37–55°S estimate that

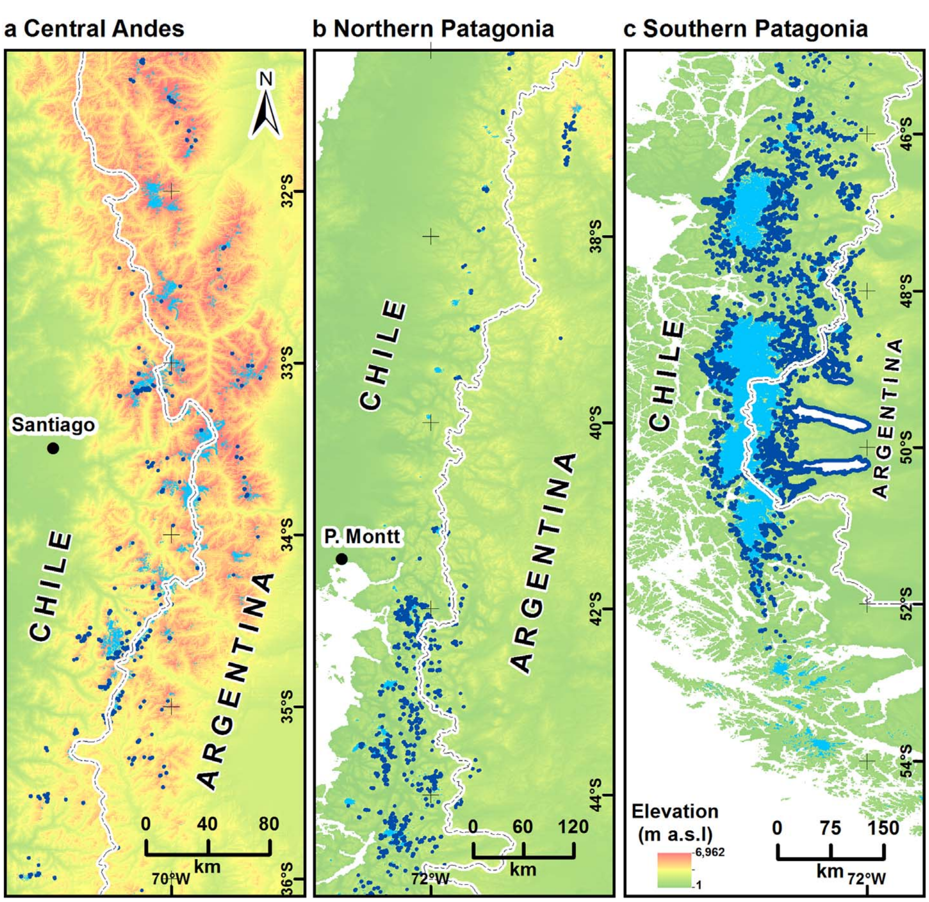

Fig. 2. Spatial distribution of glacial lakes (dark blue) detected in the Central Andes (a.), Northern Patagonia (b.) and Southern Patagonia (c.) in 2016. Regional sub-divisions are shown in Fig. 1. Glacierised areas are shown in light blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Summary of the Landsat satellite imagery used for the compilation of the 1986, 2000 and 2016 glacial lake inventories. Actual image dates for each inventory differed by ± 3 years from their target year (1986, 2000 and 2016). However, the majority of the lakes included within each inventory were delineated from images whose acquisition year matches the given target years.

Inventory	Image acquisition years	Satellite sensor	Number of images	Share of glacial lake sample within each inventory (%)
1986	1984	Landsat 5	1	3.7
	1985		8	34.3
	1986		14	41
	1987		2	21.2
2000	1999	Landsat 5	2	0.7
	2000	Landsat 7	17	44.9
	2001	Landsat 5	5	32.2
		Landsat 7	5	
	2002	Landsat 5	2	22.2
		Landsat 7	2	
2016	2013	Landsat 8	2	1.8
	2014		1	0.2
	2015		5	10.7
	2016		29	87.3

mean annual air temperatures during the 20th Century are 0.53–0.86 °C above those estimated between 1640 and 1899 (Villalba et al., 2003). However, these warming trends reported for Patagonia contrast with air temperature cooling (1950–2000) detected at low altitude meteorological stations located between 38°S and 41°S (Bown and Rivera, 2007; Falvey and Garreaud, 2009). The reductions in precipitation observed in the Central and Patagonian Andes have been largely linked to the increased frequency of negative El Niño Southern Oscillation (ENSO) events since 1976, which are associated with below average precipitation totals (Giese et al., 2002; Montecinos and Aceituno, 2003; Bown and Rivera, 2007). Important in terms of ice mass accumulation, recent warming throughout the study area may have also reduced the fraction of precipitation falling as snow (Rasmussen et al., 2007).

4. Data and methods

4.1. Data sources and glacial lake delineation

A total of 95 Landsat satellite images, with a multi-spectral spatial resolution of 30 m, were used to compile glacial lake inventories for the observation years of 1986, 2000 and 2016 (Table 2). These three target years are stated for simplicity although actual image acquisition dates for each period differ by a maximum of ± 3 years according to Landsat image availability and image quality issues, such as snow/ice cover, cloud cover and mountain shadowing. All three glacial lake inventories are available for download at https://wordpress.aber.ac.uk/glacialhazardsinchile upon request. All Landsat images were obtained from the United States Geological Survey's (USGS) Earth Explorer interface (http://earthexplorer.usgs.gov/). To improve the accuracy of the temporal glacial lake comparisons (by avoiding extensive snow and lake ice coverage), 84% (n = 80) of the images selected were acquired from January and March during austral summers. Individual glacial lakes were delineated from the Landsat imagery and given a unique identification (ID) number by a single expert utilising a manual mapping approach. Although labour-intensive, this manual approach

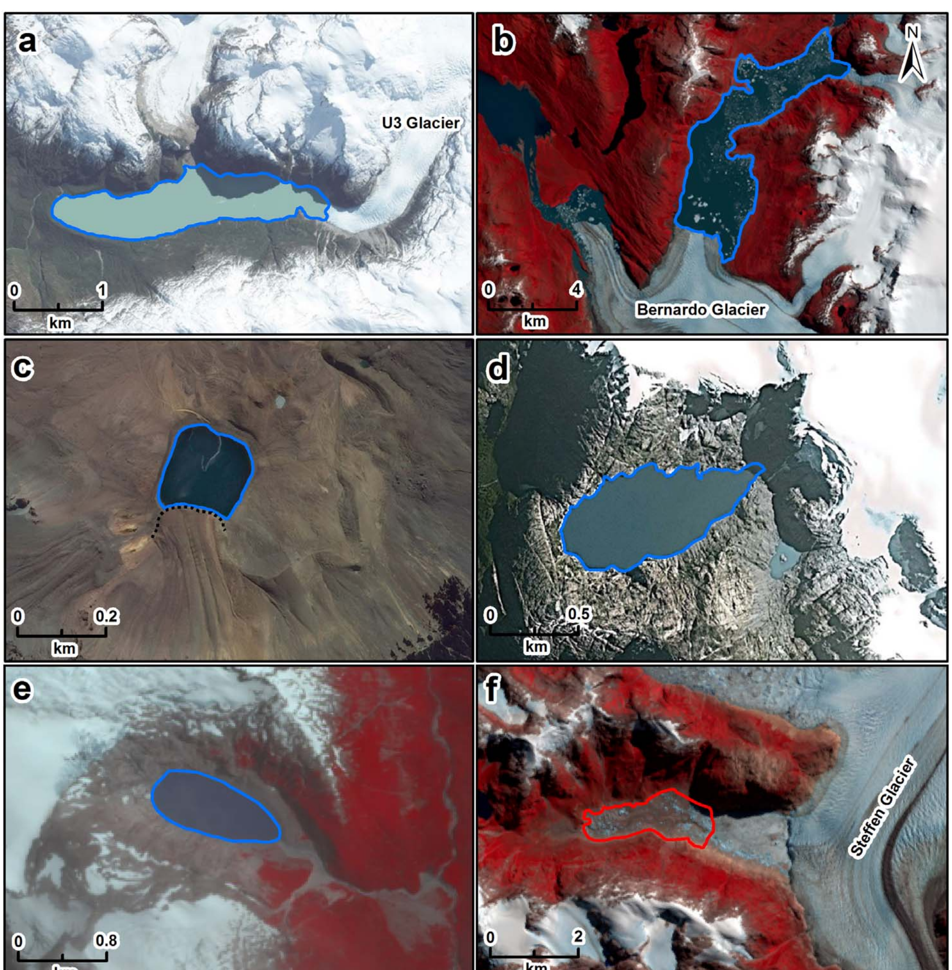

Fig. 3. Examples of glacial lakes that are: (a) moraine dammed – in contact with active ice (47.49°S, 73.52°W); (b) ice dammed (48.57°S, 73.81°W); (c) moraine dammed – in contact with in-active ice (32.59°S, 70.22°W) and (d) Rock-bar dammed – not in contact with active ice (47.13°S, 73.92°W). Images (e) and (f) depict a moraine dam failure site (42.42°S, 72.00°W – Derrumbe Lagoon (see Colavitto et al., 2012)) and an ice dammed lake drainage site (47.43°S, 73.79°W), respectively. Images (a), (c) and (d) were acquired by high resolution satellite sensors available from www.digitalglobe.com and were sourced from the Google Earth and Bing Maps. Images (b) and (e) and (f) are false colour composite pan-sharpened Landsat 8 images. The red and blue outlines represent lake margins from the 2000 and 2016 inventories, respectively. The dashed black line in image (c.) delineates the terminus of a rock glacier. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ensured consistent examination and high quality control (Zhang et al., 2015; Emmer et al., 2016). Other glacial lake monitoring studies have used semi-automated approaches based on image band ratioing and the normalised difference water index (NDWI) (e.g. Huggel et al., 2002; Bolch et al., 2011). However, these automated approaches are complicated by image quality issues, such as snow/ice cover, cloud cover and mountain shadowing.

In this study, it was assumed that contemporary glacial hazards, such as GLOFs, are most likely to be generated within the boundaries of the LIAM. Therefore, glacial lakes were only sampled if they were situated within or immediately adjacent to a given basin's LIAM extent. A similar sampling method has been used for other glacial lake inventories, such as Ukita et al. (2011). If the LIAM limits were unclear a decision was made (1) based on the surrounding glaciated basins and (2) with reference to Davies and Glasser (2012) and Masiokas et al. (2009). Located on the western side of the SPI, Lake Argentino (1365.8 km^2), Viedma (1208.1 km^2) and O'Higgins/San Martín (1037.8 km^2) are several magnitudes larger in area than any other glacial lake sampled in this study. Although their margins extend past the LIAMs of their respective glacial basins, these large lakes were included within the inventories compiled as they currently attach to actively calving outlet glaciers of the SPI.

The glacial lakes sampled were divided into three main types (Fig. 3): (1) Moraine dammed (impounded by terminal moraines); (2) Rock-bar dammed (situated within bedrock over-deepenings); and (3) Ice dammed (impounded by ice). The moraine and rock-bar dam classifications were further sub-divided according to their contact/non-contact with active ice. Moraine/Rock-bar dammed lakes in contact with in-active ice represent lakes bordering rock glaciers that have moved very little during the observation period. To ensure accuracy, glacial lake type was classified with the use of recently acquired high resolution satellite imagery (< 5 m) available within the Google Earth and Bing Maps geobrowsers. Although prevalent throughout the glaciated portions of the study area, supra-glacial lakes were excluded from the analysis in order to avoid monitoring complications associated with their seasonality. Due to the unavailability of cloud free images, glacial lakes located at latitudes > 52.6°S (including the Cordillera Darwin and Gran Campo Nevado icefields) were not included within the analysis. A small number of glacial lakes located close to the NPI and SPI were also excluded due to cloud cover (< 20 lakes).

Estimating mapping errors associated with the glacier lake area calculations presented is difficult without the use of a high resolution spatial reference source. Such errors can be influenced by several factors, including the image resolution (Landsat = 30 m), image geometric accuracy (Landsat = ~15 m (Storey et al., 2014)), expert knowledge of the user and the image quality issues stated previously. Based on a multiple digitising experiment using medium (30 m) and high resolution remotely sensed imagery (1 m), Paul et al. (2013) estimated manual mapping errors of ± 5% and ± 10% for several clean and debris-covered glaciers, respectively. Although water surfaces should in theory be easier to identify compared with debris-covered ice, the presence of mountain shadows in many of the images utilised means a more cautious uncertainty of ± 10% is assumed for all glacial lake areas totals presented. Elevation information presented was obtained from the satellite-derived ASTER GDEM which has an estimated horizontal error of ± 15 m in mountainous areas (Meyer et al., 2011).

4.2. Glacial lake volume estimation

Lake water volume cannot be derived from satellite imagery or any other data source without detailed information about the underlying basin topography. In order to calculate a first-order estimation of total water volume stored in glacial lakes across the study area for each of the three observation periods, an empirical area-volume scaling approach was therefore used which assumes a relationship between glacial lake area and volume. A number of studies have presented lake volume calculations based on area-volume relationships (e.g. O'Connor et al., 2001; Huggel et al., 2002; Loriaux and Casassa, 2013; Carrivick and Quincey, 2014). Here, water volume (V) was calculated for individual glacial lake areas (A) using the equation:

$$V = 2 \times 10^{-7} A^{1.3719} \tag{1}$$

This relationship was presented by Cook and Quincey (2015) based on area and volume data measured for 69 glacial lakes of varying size and type located in Patagonia (n = 3) and other parts of the world (n = 66). Although an area-volume regression analysis performed on this dataset resulted in a high coefficient of determination (R^2) of 0.91, Cook and Quincey (2015) note that this method of volume calculation should be used with caution as significant outliers exist related to the complex geometries of the individual lakes sampled. When the scaling approach used here (Eq. (1)) was applied to the area data measured for the 69 glacial lakes sampled by Cook and Quincey (2015), a mean error of ± 61% was calculated. This error value should therefore be considered in regards to the lake volume estimations presented in this study.

5. Results

5.1. Distribution and physical attributes of glacial lakes in 2016

Overall, 4202 glacial lakes were included within the 2016 inventory, equating to an estimated areal and volumetric water extent of 4789.7 km^2 and 1852.7 km^3, respectively (Table 3). Owing to its larger glaciated areas, 78% (3276) of these glacial lakes were located within Chile, whilst 22% (936) were located within Argentina. Importantly, three outlet lakes of the SPI (Lake Argentino, Viedma and O'Higgins/San Martín) account for 75% (3611.7 km^2) of the total glacial lake area included within the 2016 inventory. The majority of the lakes detected were classified as 'Moraine dammed – not in contact with ice' (n = 1651–39% of total) followed by 'Rock-bar dammed – not in contact with ice' (n = 1457–35% of total), with the least common being lakes in contact with in-active ice (n = 49–1% of total). Overall, 2170 (52% of total) of glacial lakes in 2016 were identified as having moraine dams, representing 13% of the total areal water extent. Lake classifications including contact with in-active ice were confined to the Central Andes region. In comparison, ice dammed lakes were detected in all three sub-regions (n = 262–6% of total) but are most common in Southern Patagonia (88%) where the majority are dammed by outlet glaciers of the SPI. Having the greatest potential to expand in size with continued glacier retreat and thinning, 783 (19%) glacial lakes were in contact with active ice (excluding ice dammed lakes), representing 86% of total lake area detected in 2016. Looking at each sub-region individually, the proportion of glacial lakes that are in contact with active ice (excluding ice dammed lakes) equates to 16% (n = 50) in the Central Andes, 15% (n = 124) in Northern Patagonia and 19% (n = 609) in Southern Patagonia. In comparison, the individual proportion of glacial lakes not in contact with active ice in the Central Andes, Northern Patagonia and Southern Patagonia equates to 59% (n = 185), 84% (n = 668) and 73% (n = 2255), respectively.

The distribution of glacial lakes sampled is shown to be heavily skewed towards the Patagonian Andes (concentrating specifically around the NPI and SPI) and South Patagonia alone accounts for 74% of all the lakes detected (Fig. 4). In terms of areal size, 63% of the glacial lakes detected (n = 2692) are < 0.04 km^2 whilst only 4% (n = 186) are > 0.6 km^2 (91% of which are located within Southern Patagonia) (Fig. 5). Sub-regionally, the areal size of glacial lakes detected varies from being generally small in the Central Andes (average size of 0.02 km^2) to relatively large in South Patagonia (average size of 1.53/0.36 km^2 with/without the three largest lakes). The largest individual lakes in the Central Andes, Northern Patagonia and Southern Patagonia cover 0.26 km^2, 1.53 km^2 and 1365.79 km^2, respectively. The elevation of the glacial lakes detected reduces considerably towards the relatively

Table 3
Summary of the amount, area and water volume of glacial lakes in the Central Andes and Northern and Southern Patagonia in 2016.

Region	Lake type	Sub-type	Number (% of total)	Total area (km^2) (% of total)	Mean area (km^2)	Lake volume (km^3)	Mean elevation (m a.s.l)
Central Andes	Moraine dammed	In contact with active ice	32 (10)	0.69 (11)	0.02	0.007	3429
		In contact with in-active ice	35 (11)	0.51 (8)	0.01	0.004	3462
		Not in contact with ice	95 (30)	1.98 (30)	0.02	0.023	3291
	Rock-bar dammed	In contact with active ice	18 (6)	0.36 (5)	0.02	0.004	3463
		In contact with in-active ice	14 (4)	0.52 (8)	0.04	0.006	3302
		Not in contact with ice	90 (29)	2.07 (32)	0.02	0.025	3530
	Ice dammed	N/A	29 (9)	0.37 (6)	0.01	0.003	3695
	Total/mean		**313 (100)**	**6.50 (100)**	**0.02**	**0.073**	**3441**
Northern Patagonia	Moraine dammed	In contact with active ice	67 (8)	6.35 (10)	0.09	0.132	1330
		Not in contact with ice	341 (43)	28.92 (45)	0.08	0.593	1321
	Rock-bar dammed	In contact with active ice	57 (7)	2.49 (4)	0.04	0.038	1381
		Not in contact with ice	327 (41)	25.88 (41)	0.08	0.564	1346
	Ice dammed	N/A	3 (0.4)	0.08 (0.1)	0.03	0.001	1908
	Total/mean		**795 (100)**	**63.72 (100)**	**0.08**	**1.329**	**1338**
Southern Patagonia	Moraine dammed	In contact with active ice	385 (12)	440.55 (9, 40[a])	1.14	35.258	866
		Not in contact with ice	1215 (39)	161.09 (3, 15[a])	0.13	5.472	1054
	Rock-bar dammed	In contact with active ice	224 (7)	3648.70 (77)	16.29	1728.977	1079
		In contact with active ice[a]	221 (7)[a]	36.99 (3)[a]	0.17[a]	2.39[a]	1091[a]
		Not in contact with ice	1040 (34)	65.51 (1, 6[a])	0.06	1.438	909
	Ice dammed	N/A	230 (7)	403.62 (9, 36[a])	1.75	80.169	484
	Total/mean		**3094 (100)**	**4719.47 (100)**	**1.53**	**1851.315**	**941**
	Total/mean[a]		**3091 (100)**[a]	**1107.76 (100)**[a]	**0.36**[a]	**2.390**[a]	**942**
	Overall total/mean		**4202**	**4789.69**	**1.14**	**1852.716**	**1203**

[a] Not including Lake Argentino (1365.8 km^2), Lake Viedma (1208.1 km^2), Lake O'Higgins/San Martín (1037.8 km^2) and any of their subsequently coalesced entities.

lowly elevated Patagonian Andes and 91% of the lakes are located < 2000 m a.s.l (Fig. 4).

5.2. Temporal development of glacial lakes between 1986 and 2016

A comparison of the 1986, 2000 and 2016 inventories allowed for the temporal development of glacial lakes in the Central and Patagonian Andes to be assessed. Overall, the number of glacial lakes increased by 1276 (43%) between 1986 and 2016, whilst glacial lake area increased by 325.76 km^2 (7%) (Table 4 and Fig. 6a). These observed changes equate to a glacial lake water volume increase of 65 km^3 over the ~30 year observation period. Both the number and total area of glacial lakes are shown to have increased during the 1986–2000 and 2000–2016 observation periods, with the rate of change for both

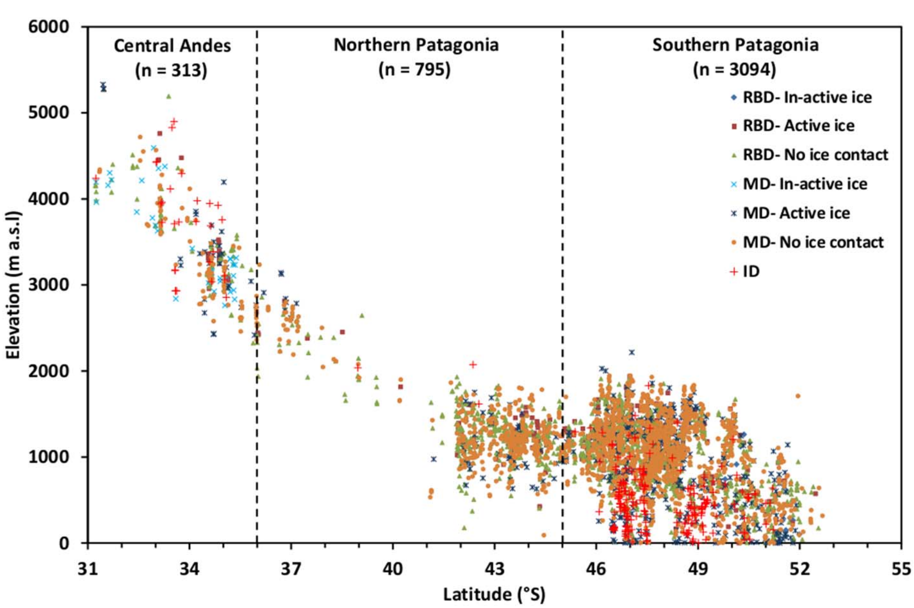

Fig. 4. Distribution of glacial lakes (n = 4202) according to latitude and elevation (RBD = rock bar dammed; MD = moraine dammed; and ID = ice dammed).

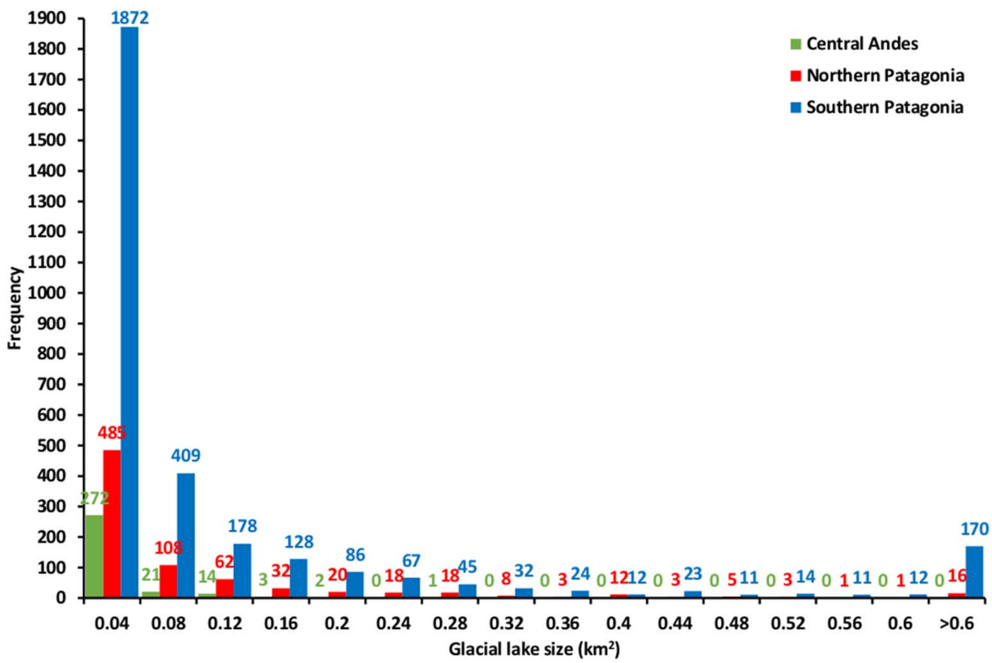

Fig. 5. Distribution of glacial lakes in the 2016 inventory according to size (n = 4202).

Table 4
Number and area of glacial lakes in the Central Andes and Northern and Southern Patagonia in 1986, 2000 and 2016.

Study area		Central Andes		Northern Patagonia		Southern Patagonia		Southern Patagonia[a]	
Latitude		31°–36°S		36°–45°S		45°–55°S		45°–55°S	
Glacial lakes 1986	Frequency	263		515		2148		2143	
	Area (km^2)	5.88		42.58		4415.47		870.2	
Glacial lakes 2000	Frequency	296		714		2483		2479	
	Area (km^2)	5.87		53.88		4559.49		970.37	
Glacial lakes 2016	Frequency	313		795		3094		3091	
	Area (km^2)	6.50		63.72		4719.47		1107.76	
Temporal Δ		Area Δ (km^2)	Area Δ (%)	Area Δ (km^2)	Area Δ (%)	Area Δ (km^2)	Area Δ (%)	Area Δ (km^2)	Area Δ (%)
1986–2000		−0.01	−0.2	11.3	27	144.02	3	100.17	12
2000–2016		0.63	11	9.84	18	159.98	4	137.39	14
1986–2016		0.62	11	21.14	50	304.00	7	237.56	27

[a] Not including Lake Argentino (1365.8 km^2), Lake Viedma (1208.1 km^2), Lake O'Higgins/San Martín (1037.8 km^2) and any of their subsequently coalesced entities.

variables remaining the same during each period (+1.3% a^{-1} and +0.2% a^{-1}, respectively).

Sub-regionally, the development of glacial lakes between 1986 and 2016 is shown to differ considerably (Fig. 6b). Containing a larger proportion of the glacial lakes within each of the inventories compiled, Southern Patagonia is shown to have undergone larger increases in total glacial lake amount and area compared to Northern Patagonia or the Central Andes. However, in relative terms, glacial lake changes in Southern Patagonia are relatively small compared to Northern Patagonia that is marked out as having undergone the largest changes, its total glacial lake area having increased by 50% between 1986 and 2016. This relatively high rate of increase was particularly evident during the 1986–2000 observation period when total glacial lake area increased by 27% compared with 3% and −0.2% for Southern Patagonia and the Central Andes, respectively. Although remaining comparatively high, the rate of total glacial lake area increase dropped considerably for Northern Patagonia during the 2000–2016 observation period, a time period characterised by lake area growth in both the Central Andes and Southern Patagonia (albeit marginally). Notably, the magnitude of the glacial lake area changes shown for Southern Patagonia are increased when removing the three largest lakes (Lake Argentino, Viedma and O'Higgins/San Martín), however, the temporal trend remains the same (Fig. 6). It is important to add that the sub-regional differences in glacial lake development shown include mapping uncertainties associated with the use of medium resolution satellite imagery (see Section 4.1). However, through applying a manual mapping approach these uncertainties have been limited and we are confident that the sub-regional trends observed have not been influenced.

Typically forming in ice marginal positions or low gradient valley bottoms recently vacated by retreating glacier snouts, the number of newly formed glacial lakes over a given time period can offer valuable insights into the magnitude of glacial change for an area. For the entire Central and Patagonian Andes, the number of newly emerged glacial lakes increased from 835 between 1986 and 2000 to 889 between 2000 and 2016 (Fig. 6c). However, sub-regionally, the rate of emergence is again shown to differ. Whilst Southern Patagonia has shown an increase in the number of glacial lakes emerging between 1986–2000 and 2000–2016 (33%), the Central Andes and Northern Patagonia have both shown large decreases of 48% and 52%, respectively. In addition to newly emerging lakes, a number of glacial lakes have also disappeared during the observation period. Not including glacial lakes that have coalesced to form larger water bodies, 162 glacial lakes were identified to have disappeared across the entire study area during the 1986–2000 observation period, with an additional 109 disappearing between 2000 and 2016. Concentrating around the NPI and SPI, the

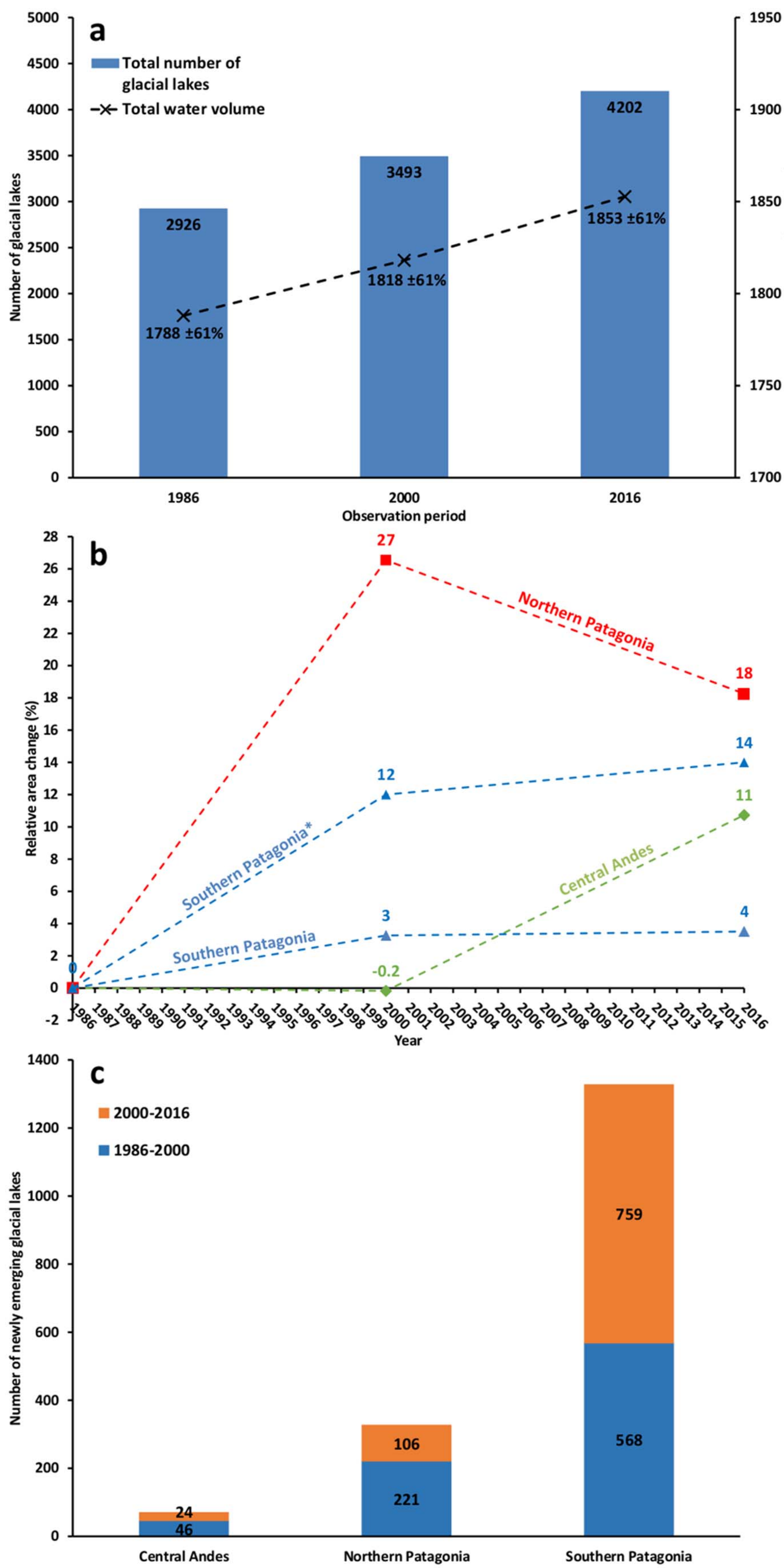

Fig. 6. (a) Evolution of total number and water volume of glacial lakes, (b) relative glacial lake area change (data labels represent relative changes between 1986–2000 and 2000–2016, respectively) and (c) number of newly emerging lakes between 1986, 2000 and 2016. Southern Patagonia* represents relative glacial lake area change in this region not including Lake Argentino, Lake Viedma Lake O'Higgins/San Martín and any of their subsequently coalesced entities.

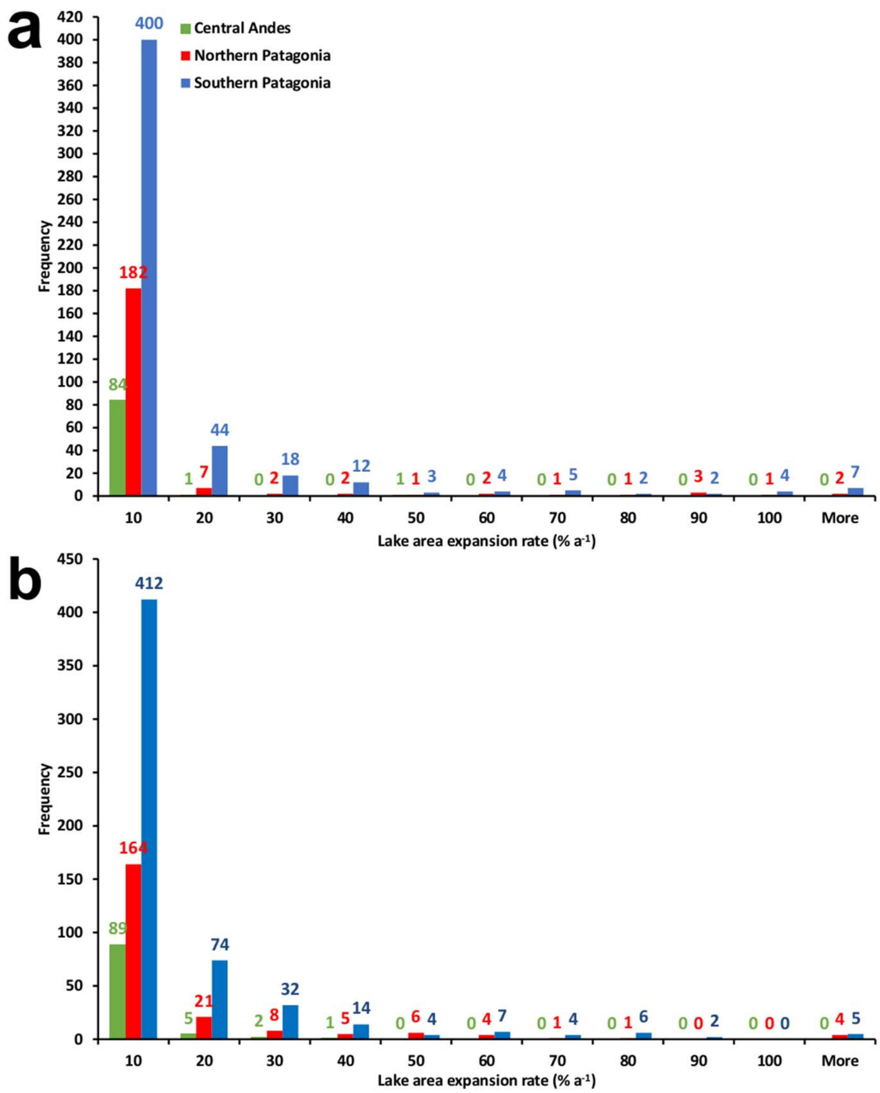

Fig. 7. Glacial lake expansion rates in the Central Andes, Northern Patagonia and Southern Patagonia observation periods (a) 1986–2000 and (b) 2000–2016.

majority of these disappearances can be attributed to ice marginal lakes that have drained permanently as a result of glacier downwasting. The remaining glacial disappearances are likely the result of non-catastrophic processes such as sediment infilling, progressive drainage and/or evaporation, reduced water input and in some instances infilling by volcanic debris. The influence of many of these factors on glacial lakes is likely to change as nearby glacier snouts retreat up-valley. None of the GLOF events observed in this study (see Section 5.3) resulted in the complete drainage of the associated glacial lake.

5.3. Rapidly expanding glacial lakes and newly observed GLOF events

A number of glacial lakes included in the three inventories presented have shown large rates of expansion during the 1986–2000 and 2000–2016 observation periods. These include long-existing (detected in 1986 and 2016) glacial lakes, lakes identified both in 2000 and 2016, and post-2000 newly emerged lakes. In terms of long-existing lakes, out of a total of 2624, 125 (5%) have expanded by a rate of > 10% a^{-1} between 1986 and 2016, 98% of which are located in either Northern or Southern Patagonia (Fig. 7a). For the 2000 to 2016 period, 206 lakes were identified as having expanded by a rate of > 10% a^{-1} (Fig. 7b). The spatial distribution of these 206 lakes is shown in Fig. 8b, including the location of three lakes of interest. These specific lakes of interest have grown by 23% a^{-1} (ID = 39), 140% a^{-1} (ID = 4887) and 192% a^{-1} (ID = 2866) between 2000 and 2016 and represent the most rapidly expanding lakes adjoining calving glaciers in the Central Andes, Northern Patagonia and Southern Patagonia, respectively. The areal extent of each of these lakes has been mapped at a higher temporal resolution and is plotted in Fig. 9, highlighting the differences in lake size and expansion rate in the context of their sub-regional location. Of particular interest, the Northern Patagonia lake (ID: 4887), which is impounded by a terminal moraine of Ventisquero Negro glacier, is shown to have reduced in area between 2005 and 2010 after a period of rapid expansion. This sudden reduction in lake area by ~0.13 km^2 was the result of a large GLOF event that occurred in May 2009, releasing an estimated $10 \times 10^6 m^3$ of water downstream (Worni et al., 2012). Analysis of this event by Worni et al. (2012) suggests that the GLOF was most likely triggered by heavy precipitation, resulting in high lake outflow which led to dam erosion and finally to dam failure. Despite the GLOF event, this glacial lake has continued to expand between 2010 and 2016 in response to the retreat of Ventisquero Negro's calving glacier front. The 2000 to 2016 observation period was also marked by the emergence of a number of new and relatively large glacial lakes, the locations of which are shown in Fig. 8a. Overall, 122 of these newly emerged lakes have areal extents larger than 0.04 km^2 (0–0.04 km^2 representing the modal size category for the 2016 glacial lake inventory), with 41 (34%) having a moraine dam and 53 (43%) adjoining a calving glacier.

The analysis of multi-temporal Landsat, Bing Maps and Google Earth imagery during the compilation of the glacial lake inventories has

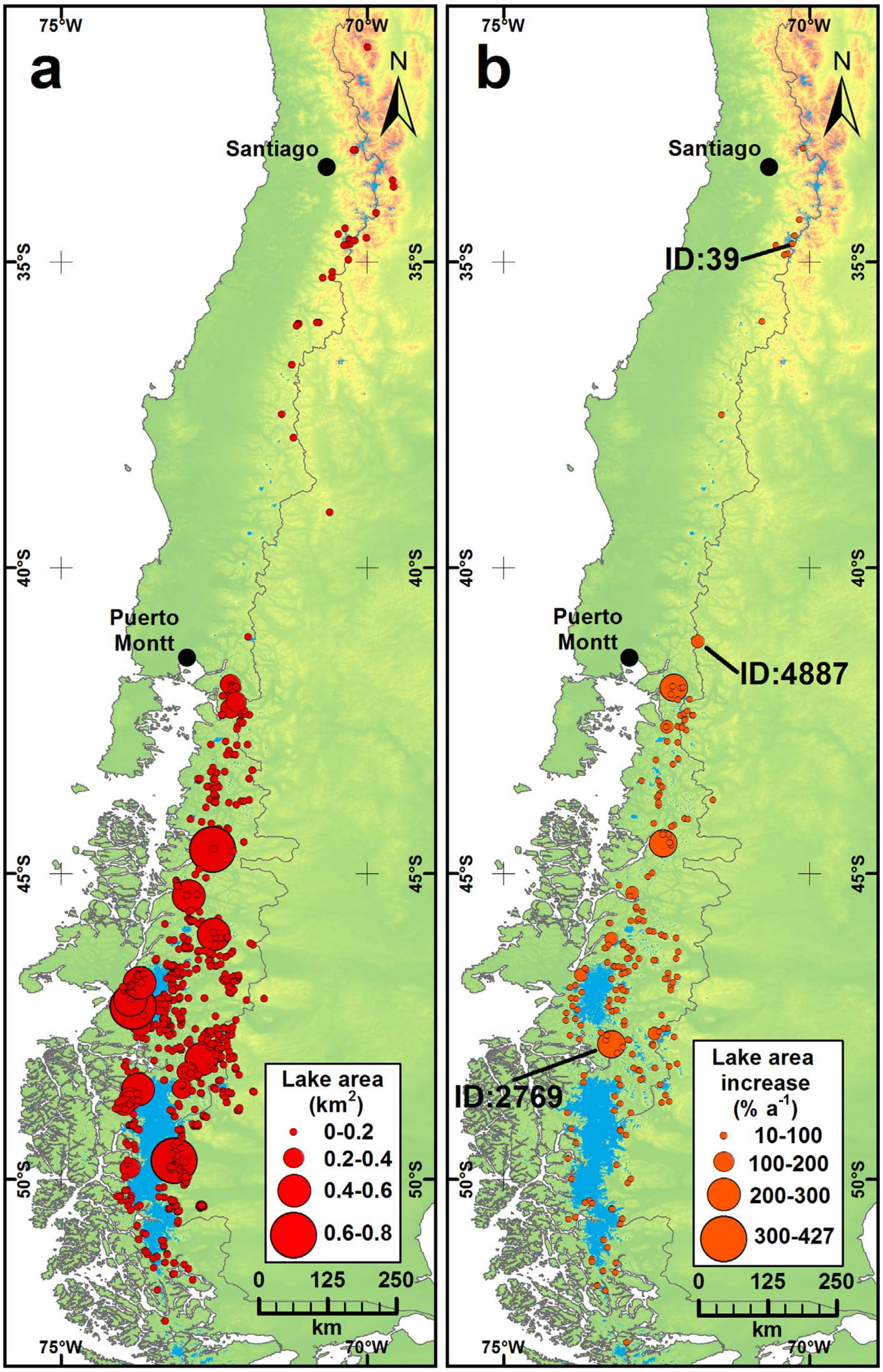

Fig. 8. (a) The size and distribution of glacial lakes that have emerged between 2000 and 2016 and (b) the growth magnitude and distribution of rapidly expanding (> 10% a^{-1}) glacial lakes existing in 2000 and 2016 (including the locations of the three lakes shown in Fig. 11). Glacierised areas are indicated in light blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

offered a good opportunity to identify previously un-reported GLOF events across the study area. Such events are often distinguishable in medium to high resolution satellite imagery by distinct v-shaped trenches cut into moraine dams and/or the presence of relatively large debris plains (Fig. 3e). As part of their review of glacial hazards in the Chilean and Argentinian Andes, Iribarren Anacona et al. (2015b) identified 16 lakes that had experienced moraine dam failures between 1913 and 2006. Table 5 lists the location and general characteristics of an additional 21 glacial lake moraine dam failures and/or overtoppings that have been identified in this study. Table 5 also includes information on the Derrumbe Lagoon (42.43°S, 72.00°W), Argentina, which failed sometime 1952 and 1964 and is described by Colavitto et al. (2012). Of the 21 newly identified GLOF events, one was located in the Central Andes, four were located in Northern Patagonia and 15 were located in Southern Patagonia. Since 2000, at least eight GLOF events have taken place, with the most recent event having occurred in the Chileno valley, Southern Patagonia (46.53°S, 73.12°W), sometime between December 2015 and January 2016.

Globally, ice dammed lakes represent the most common source of glacier outburst floods (Carrivick and Tweed, 2016). In the Central and Patagonian Andes these types of events are centred around the NPI and SPI where lakes have formed in marginal positions around several of the large outlet glaciers. Table 6 lists the location of NPI and SPI ice dammed lakes that have shown evidence of sudden and/or gradual drainage events between 1986 and 2016. These events were marked by changes in lake size and/or the presence of newly exposed lake basins

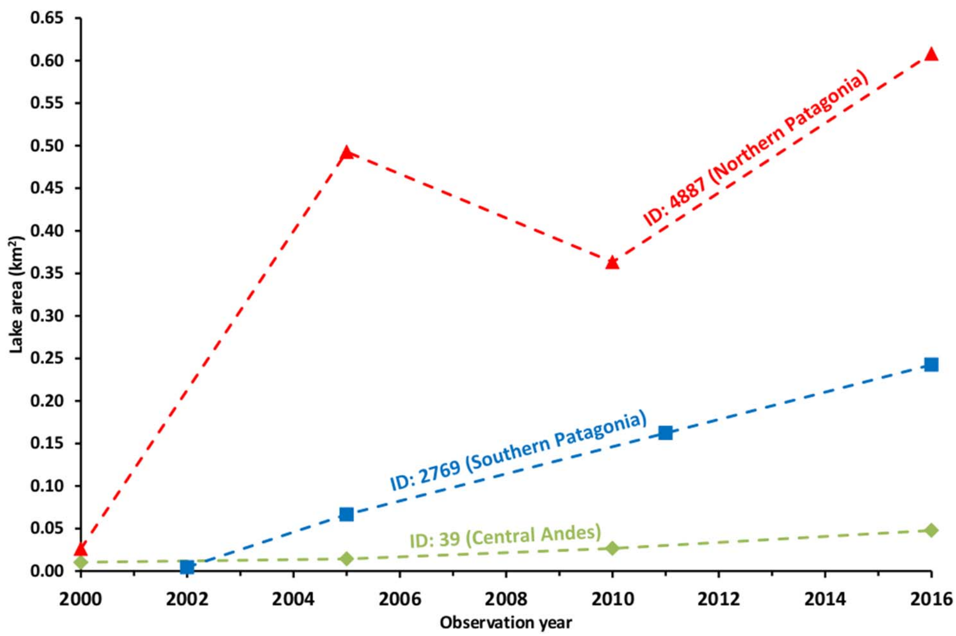

Fig. 9. Areal changes between 2000 and 2016 for the most rapidly expanding glacial lakes adjoining calving glaciers in the Central Andes, Northern Patagonia and Southern Patagonia.

which, in some cases, were scattered with grounded icebergs. The largest of these drainage events occurred at Viedma glacier, SPI, where an ice dammed lake was observed to have reduced in area from 7.15 km^2 in 2000 to 1.53 km^2 in 2016. As reported for Lago Catchet II, which is adjacent to Colonia glacier, NPI (e.g. Friesen et al., 2015), many of the ice dammed lakes listed in Table 6 are likely to have undergone repeated drainage events over the 31 year observation period.

6. Glacial lake development in the Central and Patagonian Andes

The evolution of glacial lakes in the Central and Patagonian Andes is highly dependent on the interlinkages between local topography, meteorology, climate change and glacier change. On a regional basis, the overall increase in size and number of glacial lakes across the study area between 1986 and 2016 comes in response to widespread glacier retreat and thinning brought about by increasing air temperature and changes in the amount of solid precipitation (Masiokas et al., 2009; Davies and Glasser, 2012; Malmros et al., 2016). Such behaviour is in accordance with post-LIA trends observed in other glacierised mountain regions, such as the Peruvian and Bolivian Andes (Emmer et al., 2016; Cook et al., 2016), the European Alps (Emmer et al., 2015), the Pamirs (Mergili et al., 2013) and the Himalayas (Wang et al., 2014). The subregional differences in glacial lake change shown in this study, however, reflect the diverse topographical and climatic settings of the Central and Patagonian Andes and their influence on the development and longevity of glacial lakes in this mountain environment.

Emmer et al. (2016) divides the life cycle of glacial lakes into three phases: glacier advance, glacial retreat and non-glacial. The first of these phases is characterised by glacially-driven bedrock over-deepening and lateral/terminal moraine construction. Both of these processes support the development and growth of glacial lakes during the initial stages of the second phase as glacier snouts begin to retreat upvalley. With continued glacial retreat and in some instances deglaciation, former proglacial lakes may then turn into seasonal or endorheic water bodies during the final phase of the cycle or disappear completely in a non-catastrophic way. In the highly elevated Central Andes, the number, size and expansion of glacial lakes has been constrained by several factors. The glacial advances of the LIA, for example, were likely to have been limited by the semiarid climate, which placed a constraint on the number and areal extent of glaciers in this region relative to those located in the Patagonian Andes. This is evidenced when comparing the LIAM extents presented for glaciers of the Central and Patagonian Andes within Masiokas et al. (2009) and Davies and Glasser (2012). Additionally, the majority of the glaciers located in the Central Andes are relatively small and have retreated towards high elevation accumulation zones, in doing so, vacating bedrock areas that are too steep to support glacial lake development. Where larger glaciers have formed in the Central Andes, these in many cases, have been characterised by frequent length oscillations and glacier surges over the past century (Espizúa, 1986; Llorens, 2002; Masiokas et al., 2009; Wilson et al., 2016b), behaviour that is unfavourable for the formation of moraine dammed lakes (Iturrizaga, 2014). Another consideration in regards to the existence of glacial lakes in the Central Andes is that a large proportion of the glacierised area in this region is made up of rock glaciers (Janke et al., 2015) whose location (steep topography), development, structure and dynamics do not facilitate the growth of glacial lakes such as those detected in the Patagonian Andes. It is important to add that there are also a large number of debris-covered glaciers in the Central Andes (Masiokas et al., 2009) on which, in many cases, supra-glacial lakes have formed. These supraglacial lakes were not considered in this study but in most cases were observed to be small and are likely to be seasonal and/or transient (existence related to the underlying glacier flow regime and associated through-ice drainage) in nature.

In comparison to the Central Andes, glacial lakes in Northern and Southern Patagonia are more numerous and have, in general, undergone larger absolute changes in area. These regions have also seen the emergence of far greater number of new glacial lakes since 1986. The enhanced development and growth of glacial lakes in these two regions is again linked to the scale of the glacier advance during the LIA. Facilitated by higher levels of solid precipitation compared with the Central Andes, glacierised areas in Patagonia were able to achieve LIAMs that extended for considerable distances along relatively flat valley bottoms (Davies and Glasser, 2012). This climatic/topographic pre-conditioning enabled the development and growth of proglacial lakes during the 20th century in response to widespread retreat of glacier snouts. Development and growth of glacial lakes in Northern and Southern Patagonia, as in the Central Andes, is thus dependant on the rate of glacier retreat and the availability of low gradient ice areas.

Analyses of glacier fluctuations in Chile and Argentina have identified Northern Patagonia as having undergone considerable reductions in glacier coverage over the past 100 years (Masiokas et al., 2009; Paul

Table 5
GLOF events identified in the Central and Patagonian Andes using Landsat imagery (~1986, ~2000 and ~2016) and high-resolution imagery available within Bing Maps and Google Earth (see Fig. 1). These GLOF events have been identified in addition to the 16 events reported in Iribarren Anacona et al. (2015b). The Derrumbe lagoon GLOF (42.42°S, 72.00°W), Argentina, has been previously described by Colavitto et al. (2012). In some cases, the lakes listed have grown in size and/or refilled post-GLOF.

Lat. (°S)	Lon. (°W)	Outburst date	Lake type as of 2016[a]	Pre-outburst size (km^2) *(observation date)*	Current size (km^2)	Elevation (m.a.s.l)	Terrain features
35.97	70.81	> 04/02/2009– < 04/01/2014	MD	0.38 *(2000)*	0.022	2650	Moraine breach and outwash plain
36.85	70.45	< 26/03/1986	MD	–	0.044	2682	Moraine breach
42.30	72.11	> 21/02/2000– < 16/12/2009	MD	0.02 *(2000)*	0.006	990	Moraine breach and outwash plain
42.42	71.92	< 07/03/1985	MD	–	0.038	1437	Moraine breach and outwash plain
42.43	*72.00*	*> 1952– < 1964*	*MD*	–	*0.464*	*994*	*Moraine breach and outwash plain*[c]
43.95	72.11	> 07/03/1985– < 21/02/2000	MD-ice calving	0.03 (1985)	0.058	881	Moraine breach and outwash plain
44.44	72.39	< 07/03/1985	MD	–	0.565	670	Moraine breach and outwash plain
45.92	72.56	> 08/03/2000– < 01/02/2015	MD-ice calving	0.10 *(2000)*	0.070	1224	Moraine breach and outwash plain
46.08	72.41	> 07/03/1985– < 08/03/2000	MD	0.01 *(1985)*	0.004	1327	Moraine breach
46.43	72.52	> 07/03/1985– < 08/03/2000	MD	0.05 *(1985)*	0.052	959	Moraine breach and outwash plain
46.52	72.42	< 07/03/1985	MD	–	0.208	1345	Outwash plain
46.53	72.84	< 07/03/1985	MD	–	0.077	881	Moraine breach and outwash plain
46.53	73.12	> 04/12/2015– < 07/01/2016	MD-ice calving	0.03 *(2002)*	0.878	230	Outwash plain
46.53	72.43	> 08/03/2000– < 23/02/2010	MD	0.02 *(2000)*	0.022	1309	Moraine breach and outwash plain
46.62	73.03	> 08/03/2000– < 01/01/2013	MD-ice calving	0.003 *(1986)*	0.037	1062	Moraine breach and outwash plain
47.50	73.41	< 09/02/1987	MD-ice calving	–	0.612	496	Moraine breach and outwash plain
49.41	73.01	< 14/01/1986	MD	–	0.076	935	Moraine breach and outwash plain
49.70	73.11	> 12/03/2001– < 22/10/2014	MD	0.64 *(2001)*	0.541	309	Moraine breach and outwash plain
49.74	73.09	> 12/03/2001– < 02/02/2016	MD	0.09 *(2002)*	0.125	871	Moraine breach and outwash plain
49.81	73.09	> 09/12/1986– < 12/03/2001	MD-ice calving	–	0.092	670	Moraine breach
49.82	73.90	> 26/12/1984– < 12/03/2001	MD-ice calving	0.35[b] *(1984)*	0.552	87	Moraine breach and outwash plain
50.95	72.96	< 09/12/1986	MD	–	0.581	830	Moraine breach and outwash plain

[a] MD = Moraine dammed.
[b] Cumulative total (more than one lake present within corresponding basin).
[c] Described previously by Colavitto et al. (2012).

Table 6
Ice dammed lakes of the NPI and SPI which have drained between 1986 and 2016.

Lat. (°S)	Lon. (°W)	Lake type	Glacier	Maximum size (km^2) (observation date)	Current size (km^2)	Elevation (m.a.s.l)	Terrain features
46.83	73.86	Ice dammed	San Quintin (NPI)	0.72 (1987)	0.38[a]	411	Drained lake basin
46.87	73.97	Ice dammed	San Quintin (NPI)	0.11 (2001)	0.02[a]	268	Drained lake basin
46.91	73.89	Rock-bar dammed	San Quintin (NPI)	0.11 (1987)	0.02	377	Drained lake basin
47.03	73.84	Ice dammed	Benito (NPI)	0.60 (2001)	0.44	148	Drained lake basin
47.15	73.37	Ice dammed	Colonia (NPI)	0.89 (1987)	0.35[a]	305	Drained lake basin
47.19	73.26	Ice dammed	Colonia (NPI)	3.89 (2002)	0.00	421	Drained lake basin
47.25	73.83	Ice dammed	HPN2 (NPI)	1.38 (2001)	0.00	175	Drained lake basin
47.27	73.79	Ice dammed	HPN2 (NPI)	0.29 (1987)	0.00	529	Drained lake basin
47.29	73.77	Ice dammed	HPN2 (NPI)	0.37 (2001)	0.05[a]	669	Drained lake basin
47.32	73.88	Ice dammed	HPN3 (NPI)	1.04 (2001)	0.37	122	Drained lake basin
47.35	73.65	Ice dammed	Steffen (NPI)	0.49 (1987)	0.27	686	Drained lake basin
47.44	73.79	Ice dammed	Steffen (NPI)	5.05 (1987)	0.00	250	Drained lake basin
48.78	73.97	Ice dammed	Occidental (SPI)	0.67 (2000)	0.23	411	Drained lake basin
48.89	73.99	Rock-bar dammed	Greve (SPI)	0.81 (1986)	0.31	413	Drained lake basin
48.93	73.97	Ice dammed	Greve (SPI)	3.96 (1986)	1.86[a]	321	Drained lake basin
49.55	73.05	Ice dammed	Viedma (SPI)	7.15 (2000)	1.53	311	Drained lake basin

[a] Cumulative total (more than one lake present within corresponding basin)

and Mölg, 2014) and this is reflected by the large relative increases in glacial lake areas detected for this region since 1986. However, the temporal analysis of glacial lake changes for this region between 2000 and 2016 revealed two important factors; (1) the rate of glacial lake area increase has reduced considerably; as has (2) the number of newly emerging glacial lakes. These factors may indicate that glacial lake development in Northern Patagonia is moving towards the non-glacial phase discussed by Emmer et al. (2016) as glaciers increasingly detach from their proglacial lakes and recede towards steeper topography. As of 2016, for example, 84% of glacial lakes in Northern Patagonia were not in contact with ice and, as a result, the overall rate of glacial lake area increase in this region is unlikely to increase in the future unless offset by an increase in the number of newly emerging lakes. Similar to Northern Patagonia, Southern Patagonia also has a high percentage of glacial lakes not in contact with ice in 2016 (73%). However, the growth and continued emergence of glacial lakes in this region in the near future is likely to be sustained due to the larger areal extent of many of its glaciers.

One important consideration, in terms of future glacial lake development in Southern Patagonia, is that the behaviour of some of the tidewater and freshwater calving outlet glaciers of the NPI and SPI is decoupled from the regional climate signal, responding instead to individual calving cycles. As a result, a number of glaciers have undergone periods of advance, stability and rapid retreat since the 1940s that have differed in timing and magnitude (Casassa et al., 1997; Aniya, 1999; Rignot et al., 2003; Rivera et al., 2012). Having been identified as a surging glacier, Pio XI glacier (SPI) is also of interest as it has experienced large frontal advances between 1945 and 2016 (Wilson et al., 2016a). This period of advance resulted in the formation of Lake Greve, the largest ice dammed lake detected in 2016 (201 km^2), which would be at risk of draining into the Eyre Fjord if Pio XI experienced a prolonged period of frontal retreat in the future.

In contrast to Northern and Southern Patagonia, total glacial lake area in the Central Andes is shown to have reduced during the 1986–2000 period before increasing during the 2000–2016 period. However, this trend is not representative of glacial lake change in this sub-region and is largely influenced by the complete drainage of the two largest glacial lakes detected in the 1986 inventory. With a total area of 0.6 km^2, these two lakes represented 10% of the 1986 glacial lake areal coverage detected in the Central Andes and seem to have drained in a non-catastrophic manner between 1986 and 2000. If these two lakes are excluded from the change analysis, total glacial lake area is then shown to have increased by 11% between 1986 and 2000, an amount that is equal to the rate of increase shown for the 2000–2016 period. It is worth noting, however, that the distribution of glacial lake area increases in the Central Andes between 2000 and 2016 is spatially limited, with 53% of the area increases attributed to lake expansion and lake emergence being brought about by only 10 individual lakes. Considering the (1) high percentage of glacial lakes not in contact with active ice (74%), (2) limited number of expanding glacial lakes, (3) considerable decrease in the number of new lakes emerging during the 2000–2016 period and (4) the localised constraints to glacial lake development related to topography and glacier size, it is therefore unlikely that the rate of glacial lake area growth in the Central Andes will increase significantly in the future.

6.1. Glacial lake monitoring and future GLOF risk assessment

The glacial lake monitoring efforts presented in this study represent the first step towards a more detailed assessment of GLOF risk in the Central and Patagonian Andes of Chile and Argentina. In order to compile such an assessment, ideally a rigorous geomorphic investigation would be performed in order to identify and quantify GLOF threshold and trigger parameters on a basin-to-basin scale (see Reynolds, 2014). Previous studies have attempted to rank glacial lake failure susceptibility and determine downstream impacts using medium resolution satellite-derived imagery and elevation data as part of quantitative, semi-quantitative and qualitative GLOF hazard, vulnerability and risk assessment approaches (e.g. Iribarren Anacona et al., 2014; Emmer et al., 2016; Rounce et al., 2016). During such approaches, GLOF generation parameters and their relative importance for a given area are chosen either (1) statistically (quantitatively) - based on physical measurements and/or observations, (2) subjectively (qualitatively) - according to the experience of the researchers, or (3) through a combination of statistical and subjective assessment (semi-quantitatively) (Emmer and Vilimek, 2013). These previous studies, however, were performed over relatively small areas and the applicability of similar GLOF risk assessment approach using the entire 2016 glacial lake inventory, for example, is limited by the large number of lakes included (n = 4202). Together with the information available about past GLOF events, the glacial lake analysis presented is therefore of most use for the general identification of lakes of interest in the Central and Patagonian Andes where GLOF risk assessments performed using remotely sensed data and/or field-based investigations would be of most benefit. Analysis of the GLOF events that have occurred in Chile and Argentina since 1913, for example, suggests that rock-bar dammed glacial lakes, which make up 42% (n = 1770) of the 2016 inventory, are the least likely to produce outburst floods, with not a single event having been reported. Furthermore, rock-bar dammed lakes only account for 23% of the total glacial lake area increases identified between

2000 and 2016. This ratio of GLOF occurrence according to lake type, however, has been shown to change through time for other glacierised regions in the world. In Peru, for example, Emmer et al. (2016) noted that GLOFs originating from rock-bar dammed lakes began to dominate in frequency from the beginning of 21st century. It is also important to add that the visibility and identification of rock-bar dammed GLOF events within past satellite imagery is hindered as they lack distinctive moraine breaches and tend to have reduced debris plains.

Previous information regarding GLOF events both in South America and other parts of the world suggests that moraine dammed lakes are most likely to produce outburst events, particularly those in contact with calving ice fronts (Mergili and Schneider, 2011; Wang et al., 2012; Iribarren Anacona et al., 2014). By focusing on this latter lake type, the number of glacial lakes for which a further assessment could be beneficial would reduce to 484 (as of 2016). Of this total, 58 lakes were identified as having increased rapidly in area between 2000 and 2016 ($>10\%\ a^{-1}$), which is another factor commonly associated with increased likelihood of failure (Bolch et al., 2011; Rounce et al., 2016). However, the use of such factors as first order methods for the identification of hazardous lakes has its limitations. The assumption that glacial lake growth leads to an increased likelihood of moraine dam failure, for example, can be misleading and is dependent on the geometry and structure of a given dam and the surroundings of the impounded lake. For example, although lake growth can result in an increased proximity to potential hazards (e.g. ice/rock avalanche prone areas (Rounce et al., 2016)), this is offset by subsequent increases in the energy required by trigger events to initiate a dam failure and/or overtopping in a larger body of water. Equally, despite being the source of all the GLOF events reported in Chile and Argentina, the assumption that moraine dammed lakes are inherently unstable is also questionable. Out of the 2170 moraine dammed lakes detected in 2016, for example, only 38 are known to have produced GLOFs, equating to a failure rate of only 1.7%. Furthermore, to date, only two of the 206 glacial lakes that have been identified as rapidly expanding (increasing in area by $>10\%\ a^{-1}$) between 2000 and 2016 have produced a GLOF, lessening the argument that lake growth is a key factor in the generations of GLOFs.

Out of the three sub-regions included in this study, the likelihood of future outburst events is highest within the Chilean territories of South Patagonia because this region has the largest frequency of reported outburst events, number of glacial lakes of all types, and glaciated area. Additionally, this region has experienced an increased rate of glacial lake emergence since 2000. South Patagonia also contains the largest number of ice dammed lakes, some of which have drained and re-filled repeatedly since 1986. However, although future outburst likelihood is high, the socio-economic vulnerability to such events in South Patagonia is relatively low, with the majority of the areas immediately downstream of glacierised basins remaining remote and lowly populated. In comparison, socio-economic vulnerability to outburst events is highest in the Central Andes whose basins feed heavily populated downstream areas (e.g. Santiago de Chile) and include important infrastructure located nearby mountain rivers (e.g. roads, bridges and communication networks). However, due to their relatively small size and limited growth potential, glacial lakes in the Central Andes are unlikely to generate outburst events large enough to threaten lowland areas and would only pose a risk to human activities, such as mining, undertaken in their immediate vicinity. Furthermore, in response to heightened loss of low gradient ice areas and reductions in the number of emerging glacial lakes, the likelihood of future outburst events in the Central Andes, as in Northern Patagonia, may have reduced relative to the past three decades. However, it is important to add that GLOF risk in each of the sub-regions studied will change in response to future socio-economic developments (e.g. tourism, agriculture, hydropower and mining activities) and possible changes in the frequency of outburst trigger events. The likelihood of future mass movements, for example, may increase due to the continued destabilisation of mountain slopes as a result of glacier retreat and the climate-induced degradation of permafrost and ice-cored moraines (Holm et al., 2004; Gruber and Haeberli, 2007). Continued glacial lake monitoring is therefore recommended throughout the Central and Patagonian Andes in combination with more detailed glacial hazard assessments where possible.

7. Conclusion

Landsat satellite imagery and information available in Google Earth and Bing Maps were used to compile the first glacial lake inventories of the Central and Patagonian Andes for the 1986, 2000 and 2016 observation periods. Glacial lakes across the study area were shown to have increased both in number (43%) and areal extent (7%) during the ~30 year observation period. As of 2016, 4202 glacial lakes were present within three sub-regions (Central Andes, Northern Patagonia and Southern Patagonia), equating to an estimated water volume of $1853\ km^3$. The distribution of these glacial lakes is heavily skewed towards the more glacierised Chilean territories of Southern Patagonia. Furthermore, sizes of the individual glacial lakes were shown to vary from relatively small in the Central Andes to generally large in Southern Patagonia, where the largest lake has an areal extent of $1365.7\ km^2$ in 2016. In terms of glacial lake type, 52% (n = 2170) of lakes present in 2016 were impounded by a moraine dam, representing 13% of the total areal water extent. Having the greatest potential for future change, 19% (n = 783) of the rock-bar and moraine dammed lakes present in 2016 were in contact with active ice, whilst 6% (n = 262) were impounded by ice dams. In addition to the observation of a number of non-catastrophic glacial lake reductions and disappearances, the temporal analysis presented also identified 21 previously unreported GLOFs, including at least eight events that have occurred since 2000. However, out of the glacial lakes that have been identified as rapidly expanding between 2000 and 2016 (n = 206), to date only two have produced a GLOF, lessening the argument that lake growth is a key factor in the generations of GLOFs.

Despite the general trend of glacial lake growth throughout the Central and Patagonian Andes, sub-regionally the rate of glacial lake development is shown to differ. In comparison with the Central Andes, for example, the total glacial lake area detected in Northern and Southern Patagonia has undergone larger absolute changes between 1986 and 2016. Northern Patagonia, in particular, has been marked out as having experienced the largest glacial lake changes, its total lake area increasing by 50% between 1986 and 2016. In contrast to the other two sub-regions, however, the rate of areal growth of glacial lakes in Northern Patagonia has reduced considerably between 2000 and 2016. Moreover, the number of newly emerging glacial lakes in Northern Patagonia during this latter period is shown to have declined, a trend also observed in the Central Andes. This variance in glacial lake development is likely brought about by differences in topography, meteorology, climate change, rate of glacier change and the availability of low gradient ice areas and will influence the rate of lake growth and the likelihood of outburst events in each of the sub-regions in the future. With regard to possible hazards, the likelihood of future outburst events is highest in Southern Patagonia, which contains the largest number of moraine- and ice-dammed lakes, whilst the potential socio-economic impact of future outburst events is highest in the Central Andes. Glacial lakes in the Central Andes, however, are unlikely to threaten the highly populated downstream lowlands due to their small size and limited growth potential. Despite the differences shown, continued glacial lake monitoring is nonetheless recommended for the entire Central and Patagonian Andes, particularly in light of the GLOF risks posed towards future developments in agriculture, tourism, hydropower and mining in these mountainous areas. In this regard, the study presented represents an important reference dataset that can be used to inform more detailed glacial hazard assessments for selected areas of interest.

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